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SUPPORTING RESEARCH AND TECHNOLOGY FOR AUTOMOTIVE STIRLING ENGINE DEVELOPMENT

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Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Solar Applications
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Prepared for
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By William A. Tomazic

Abstract

The technology advancement topics to be described are a part of the supporting research and technology (SRT) work being conducted to support the major Stirling engine development program. This support focuses on developing alternatives or backups to the engine development work in critical areas. These areas are materials, seals, controls, combustors, and system analysis. A brief status report on each of these key areas will be presented. Specific objectives and planned milestone schedules for future activities as now envisioned are described. These planned SRT activities will be related to the timeline of the engine development program that they must support.

Introduction

The objective of the Stirling SRT work is to develop technology in support of Stirling engine development. This work is intended to provide "backup" alternatives to the approaches being followed in the engine development contract in critical areas such as seals and materials. In some cases, new fundamental relationships needed for design of advanced components or subsystems will be generated. In others, direct experimental alternative approaches to critical component development will be carried out.

Figure 1 shows the overall Stirling SRT schedule with the engine development milestones shown along the top. It is our plan to provide backup or alternative components in time for application to the Mod II engine development should they be needed.

Seals

The seals SRT effort will develop technology for improved shaft sealing systems for automotive Stirling engines. Primary emphasis will be on sliding seal concepts and on pumping ring concepts. The investigative thrust will concentrate on defining and understanding the fundamental mechanisms that control seal leakage, life, and energy dissipation. The goal is to provide information which will permit the development of a sealing system that will substantially reduce leakage of the working fluid into the crankcase and prevent leakage of oil into the working fluid, while at the same time maintaining adequate lubrication for long life and low engine power loss due to friction. Current seal designs will be technically assessed and their capabilities and deficiencies defined. Studies to define the fundamental behavior for various seal system elements will be carried out. This work will result in the establishment of criteria for

advanced seal system design. Systems meeting these criteria will be built, subjected to extensive rig testing, and finally tested in an experimental engine to prove the concept. Some of the specific projects now in progress will be described briefly.

Analysis and experimental work on the fundamentals of rod seal lubrication is being carried out at Shaker Research Corp. A mathematical model for application to low modulus seals has been developed. Experimental work to measure lubrication film thickness and the friction power loss is currently being done. These will be correlated with and used to verify the analysis.

The technique being used to determine film thickness is optical interferometry. This technique can be used to measure the film thickness distribution between a coated elastomeric seal and a transparent cylinder. To do this, light is directed at the oil film between the two surfaces and the reflected light is photographed. This reflected light is composed of two parts, the beam from the cylinder-oil interface and the beam from the oil-coated rubber interface. At certain film thicknesses, these beams will cancel each other. The photograph will show these cancellations as a set of bands; the oil thickness along each band is constant and the oil film thickness change between two adjacent bands is also constant. The photograph therefore gives the oil film distribution in the contact zone. However, the absolute thickness of the film is not given. To obtain the absolute thickness of the oil film, two pictures must be taken simultaneously of the same region using two different wavelengths of light. Each wavelength produces its own interference photograph. The shift of the band pattern between the two photographs gives the absolute film thickness.

Figure 2 shows two of the interference fringe photos taken simultaneously during reciprocating seal motion (10Hz, one inch stroke). Figure 2a was taken using a .600 micron wavelength orange filter and Figure 2b with a .550 micron wavelength green filter. Analysis of the data indicates that film thickness at the fringe overlap point shown on the figure is approximately 80 microinches. Differences in film thickness from fringe to fringe can then be determined using either photo and the film profile can be defined. High quality pictures have been difficult to obtain because of the non-spectral character of the seal material which requires that it be coated, and because of the difficulties in maintaining a perfectly cylindrical and scrupulously clean transparent seal bearing surface. Refined techniques, including use of a higher intensity light source should result in better pictures. This work will continue with the objective of obtaining film thickness measurements over a variety of operating conditions and validating the analysis so as to provide information for advanced seal design. Following this work, we are planning work with higher modulus materials.

Theoretical studies of the thermodynamics and heat transfer

characteristics of reciprocating rod seals are being carried out at Carnegie-Mellon University. A description of the work and the results obtained to date will be presented by Professor William Hughes in another paper. We are also planning to initiate work this year on an experimental study of the thermal behavior of Stirling engine rod seals. The results of this work will be correlated with the analytical work of Professor Hughes and his associates in order to provide further support to the design of advanced sealing systems.

Work is currently in progress at Mechanical Technology Incorporated (MTI) to evaluate experimentally the performance and durability of hydrodynamic oil pumping seals. The initial phase of the work is to design and fabricate a test apparatus for the testing of hydrodynamic oil pumping ring seals at test conditions simulating those found in automotive Stirling engines. Figure 3 shows the test apparatus which is now being fabricated. The next phase of effort will be testing of candidate pumping ring designs over a variety of simulated engine operating conditions. The results will be compared with analytical descriptions of rod seal behavior. A duplicate test apparatus will be built and supplied to LeRC for inhouse testing.

Continued work on pumping ring analysis is also planned because of the complexity of the problem and the variety of design configurations and materials which may be employed. Some analytical work has been done at LeRC assuming a cylindrical, untapered ring with time varying clearance and a report on this work has been published. An analysis planned for initiation this year under contract will consider the pumping ring to behave as a highly flexible member when subjected to varying hydrodynamic pressures.

Testing of seal system components, and eventually of complete seal systems, will be carried out at LeRC. A basic seal test rig, which is being used at LeRC for initial seal screening and evaluation, was obtained from Ford Motor Company and then modified considerably to allow better test control and measurement. The test apparatus is shown in Figure 4. Initial checkout runs have been made and some preliminary data on current seal configurations obtained. Further test rig modifications are now being made to improve leakage measurements of working gas and lubricating oil.

Materials

The materials work is aimed at providing the materials technology required for successful development of advanced automotive Stirling engine engines. The primary effort is on development of materials and techniques to assure trouble-free operation with high temperature, high pressure hydrogen working fluid. At Stirling engine operating temperatures, hydrogen diffuses rapidly through many alloys which are otherwise attractive from a strength standpoint. This can cause excessive hydrogen loss and may also degrade the alloy properties. Materials and techniques for hydrogen containment and compatibility at

3000 psi and 1200-1700°F will be defined, evaluated, and demonstrated.

A second major objective is to develop low cost alloys for the engine hot end (cylinder head and heater tubes) which may allow engine operation at temperatures as high as 1500°F, thereby increasing performance as well as decreasing engine cost. The alloys now used in experimental engines (N-155 and HS-31) are high in cobalt content and are very expensive. The goal of this alloy development effort is to achieve equal or better high temperature strength while avoiding the use of expensive or strategic materials. This is planned to be done through modification of existing alloys which are low in strategic material content and relatively low in cost. These alloys will be developed and their properties evaluated. Once the alloys are evaluated and characterized, heater head components and assemblies will be built and tested in laboratory facilities and on research engines.

Some of the initial work done on Stirling materials has been to determine hydrogen permeability coefficients for candidate alloys under engine operating conditions. Work has been done both at LeRC and at the Illinois Institute of Technology Research Institute (IITRI). Most of the work at IITRI has been with ultra-pure hydrogen and thus probably represents the maximum permeation rates to be expected. Figure 5 shows the results obtained at IITRI for permeability as a function of temperature for several candidate alloys. These rates are at least an order of magnitude higher than acceptable for automotive use. Results of tests at LeRC indicate that lower permeation rates may occur with commercially-pure hydrogen, although still higher than acceptable for automotive use. A number of coatings to reduce permeability were also evaluated at IITRI. Although a nickel aluminide coating showed promise in reducing permeation, problems are envisioned in attempting to coat the inside of a complex heater head. This does not appear to be a practical approach at this time.

Examination at LeRC of heater tubes taken from a USS Stirling engine which had operated for over 800 hours indicated the presence of a thin carbide coating inside of the tubes which appeared to inhibit hydrogen permeation. The source of the carbon which formed the carbide is assumed to be oil which leaked past the rod seals. This suggested that it may be possible to introduce a "dopant" to the hydrogen working fluid in a Stirling engine which would provide a self-renewing barrier coating for the hot end structures. Work has begun at LeRC to evaluate this potential.

Tests were made using various dopants or impurities in the hydrogen to define their effects on permeability. Water, methane, carbon dioxide, and carbon monoxide were studied. Some of the results obtained are shown in Figure 6. Carbon dioxide and carbon monoxide gave the best results --a tenfold reduction in permeability after about 100 hrs. of exposure at 1400°F. Methane additions gave

substantially less permeability reduction, as did water vapor. Future work at LeRC will be concentrated on carbon monoxide and carbon dioxide. Studies will also be conducted at IITRI to define the effect of dopants on hydrogen permeability rates. This work has just begun. Preliminary x-ray diffraction analysis of the inner tube surfaces after dopant testing indicates the presence of oxides only. No carbides appear to be present. More detailed and extensive analysis of any films or coatings present after dopant testing will be done in future work, both at LeRC and IITRI.

Of course, addition of too much of the higher molecular weight dopant gas would result in an undesirable increase in working fluid molecular weight and a consequent decrease in engine power. An estimate of the possible loss in engine power as a function of dopant percent is shown in Figure 7. From a performance standpoint, carbon monoxide is preferred because of its lower molecular weight. In any event, it would appear that the amount of dopant added to hydrogen probably should be no more than one or two percent to avoid significant performance loss. Studies are now in progress at LeRC to define the best dopant and the appropriate concentration required to achieve the desired permeability reduction with acceptable engine performance.

The permeability testing to date with "doped" hydrogen indicates that alloys which contain strong oxide forming elements such as aluminum, columbium, or lanthanum give the greatest reduction in hydrogen permeability. Additions of these elements will be studied during the development of improved cylinder head and heater tube alloys.

Mechanical property data for candidate alloys under the proposed Stirling engine operating conditions are not now available. In particular, creep properties of potential heater head alloys in high pressure, high temperature hydrogen are required for material selection and engine design. Work is now underway at LeRC and under contract at IITRI to obtain these data.

Testing is being done at LeRC to determine the effects on creep rupture strength of aging in hydrogen at engine heater head operating temperatures. Tests are also being made in an argon atmosphere for comparison. Specimens of the candidate alloys are aged at engine operating temperatures in both hydrogen and argon (at 1 to 2 atmospheres pressure) for 3500 hrs. Tests of the first group of candidate alloys (A-286, IN800H, 316SS, Nitronic 40, and 19-9DL with N-155 included for comparison) aged at 1400°F are complete. The results indicate a reduction in rupture strength which can be specifically attributed to thermal aging but most alloys suffered no further reductions attributable to hydrogen effects. However, two alloys, Nitronic 40 and A-286, show reduction in strength after aging in hydrogen, but no reduction after aging in argon. The results obtained for these tests are shown in Figure 8. This work will

continue for other alloys which are candidates for both heater tube and cylinder head application and at the higher temperature projected for Mod II engine operation.

A contract effort at IITRI to characterize creep-rupture properties of candidate alloys at operating temperature in high pressure (200 atm) hydrogen is in the initial phases. Six iron-base alloys are currently in this program: A-286, IN800H, N-155, 19-9DL, CRM-6D, and XF-818. The creep-rupture behavior of these alloys in the temperature range from 1200°F to 1700°F will be determined in air for times from 10 to 3000 hours and in 200 atm hydrogen for 10 to 300 hours. The rupture data and specimens will be analyzed to determine the effects of high pressure hydrogen on the creep-rupture properties and microstructures of these alloys. The creep testing in air is underway and initial results, which will serve as the comparison base for hydrogen testing, should be available soon. Design of the special high pressure hydrogen creep-rupture apparatus is complete and the long lead components are in fabrication. It is expected that assembly will be begun soon. As the work continues, other candidate alloys, including those especially modified for this application, will be tested to provide the needed design data.

A new contract effort has been initiated at AiResearch Casting Company to develop a castable iron base alloy that can be used as a cylinder head material for automotive Stirling engine. The goals which have been set for this alloy are:

1. Stress for 5000 hr rupture life at 1500°F of 29 ksi.
2. Oxidation-corrosion resistance comparable to N-155.
3. Castability equivalent to HS-31.
4. Hydrogen compatibility.
5. Alloy cost less than or equal to 19-9DL.

Obviously, these are ambitious goals. It is quite possible that some compromises will have to be made as the development effort progresses. Particular areas for compromise appear to be in the stress-rupture properties and in the alloy cost. An equivalent rupture stress derived assuming engine pressure and temperature distribution based on the EPA driving cycle would be lower and may be a more realistic objective, although the potential design margin would be reduced. The cost goal, if not strictly met, should be closely approached, at least for the basic alloy material. A specific engine cost study will be required to define the critical cost limits for the cylinder head alloy.

Work is also being initiated on the development of a wrought alloy for heater head tubes. The initial effort involves modification

of 19-9DL, primarily through the addition of one or more strong oxide-forming elements such as aluminum, columbium, or lanthanum. The modification will be aimed primarily at a significant reduction in hydrogen permeability through the generation of a relatively impermeable film by action of a dopant in the hydrogen. Another effect hoped for from the modification is reduction or elimination of corrosion observed with 19-9DL in high temperatures in a combustion gas atmosphere. Tubing will be fabricated from the modified alloys and supplied to LeRC for testing in the LeRC Stirling engine simulator rig which provides the high pressure hydrogen internal atmosphere and the external combustion atmosphere at operating temperatures. These tests will allow determination of permeability, corrosion resistance, and operational strength.

Controls

The objective of the controls SRT work is to develop backup or alternative concepts and hardware for the achievement of more efficient and reliable engine power control systems. The systems to be examined will include the mean pressure control system and more advanced systems such as the variable angle swashplate control system. A large part of the effort will be in analysis and simulation. The analysis work will be closely tied to engine testing at LeRC. Results obtained from contractor engine testing will also be used. The test data will be used first to help in developing and validating the engine control simulation model. When the model is validated and operational, it will be used to guide test planning and to evaluate response, precision, and other operational aspects of engine control systems.

A Stirling engine dynamic simulation model is now being developed at LeRC. The model is intended to simulate the United Stirling P-40 engine and will be used, in combination with inhouse testing, to characterize and evaluate the current power control system. The development method is to construct two simulations: a single working space (SWS) model to define fluid behavior, and a second model with simplified assumptions on fluid behavior, but containing four working spaces and appropriate engine inertias to simulate a four cylinder engine. The approach is to then combine them into a single large controls simulation of the P-40 engine.

The single-working-space (SWS) model was developed to determine the number of control volumes (lumps) needed to represent adequately the thermodynamics of the engine. The SWS model has been written to match the wave shapes of a detailed performance model (Tew Model) previously developed at LeRC. The SWS model differs from the performance model in that the SWS model has fewer control volumes, includes momentum as well as continuity and energy dynamics, and uses constant (average) values of heat transfer coefficients and flow resistances determined from the performance model results. Comparison of the SWS model with experimental data shows reasonable agreement in

net power-speed characteristics.

A second model was built for use in studying the behavior of the total engine system. This model consists of four working spaces (FWS) between four pistons. To reduce the calculation time on the digital computer, only three control volumes are used in each working space and gas temperatures are fixed (no energy equation). The drive dynamics are also included in the FWS model. The FWS computed net power-speed characteristic agrees reasonably with experimental data. Since all four working spaces are simulated, the unique capabilities of the FWS model can be exercised to study various phenomena not easily duplicated by a single-working space model, such as supply transients (increasing and decreasing the amount of working fluid in the cycle), short circuit (braking) transients, and piston ring leakage effects.

The capabilities of both the SWS and FWS models are currently being combined in a single engine simulation which will eventually be used with a detailed control system simulation to explore various Stirling engine control concepts.

Another Stirling control simulation model is being developed under contract by Martini Engineering. This model is intended to provide rapid computation capability to facilitate obtaining quick, approximate answers. It utilizes a simpler mathematical format than the model being developed at LeRC. It is based on Dr. Martini's steady state performance model and incorporates various simplifying assumptions based on engineering data and experience.

We are now in process of purchasing the "Advenco" engine from N.V. Philips of Holland. This engine incorporates a variable swashplate to provide engine power control. Hopefully, this system will be able to provide power control over the range required for automotive operation efficiently, reliably, and with good response characteristics. Engine tests will be performed which will allow an evaluation of performance, control response, and operational characteristics relative to engines with more conventional control systems. An engine computer model will be developed and used to guide this testing and to assist in evaluating results and making comparisons with other engine types.

Combustors

The objective of the combustor SRT work is to develop new and improved combustor concepts that will have low emissions and at the same time promote improved engine efficiency through more uniform temperature distribution, reduced requirement for exhaust gas recirculation, and lower pressure loss, blower power, and overall engine size. The particular thrust of work done to date has been to investigate the feasibility of using a catalyst to promote complete combustion at lower peak temperatures and to increase the overall heat

transfer rate to the working fluid.

Tests have been conducted at LeRC with a single-tube apparatus designed to simulate the combustion and cooling environment in a Stirling engine heater head. Initial tests were done to determine the effect of simply coating existing heater head tubes with a catalyst with the expectation of combustion occurring on the tube surface at relatively low temperatures and giving high combustion-side heat transfer coefficients. Figure 9 shows the test setup used for these tests. It consists of two concentric tubes with cooling air flowing through the center tube and an air-fuel mixture through the outer tube. For the initial tests, the outside of the center tube was coated with a platinum-rhodium catalyst. The coated tube temperature was limited to the maximum design value for the Stirling engine heater tubes, approximately 1400-1500°F. Inlet temperatures for the air-fuel mixtures were 1000°F to 1300°F. Combustion efficiencies for this configuration were very low - 20 to 50 percent. Apparently, catalyst surface temperatures were too low to provide the required level of activation for complete combustion in the available length.

An alternate configuration was tested which allowed the catalytic surface to operate at a higher temperature -approximately 1900 to 2100°F. The setup is shown in Figure 10. A similar arrangement was used as for the first series of tests, but the catalyst was placed on the inner surface of the outside tube. In this configuration, the catalyst surface is cooled primarily by radiation to the cooled inner tube and a higher catalyst surface temperature is maintained. Performance was excellent. Combustion efficiencies over the range of operating conditions were from 95 to 100 percent. A high rate of heat flux to the cooling air was obtained. And, NOx levels were less than 5ppm because of the low combustion temperatures. This is a NOx emission equivalent rate two orders of magnitude lower than the Clean Air Act research standards. A report on this work is now being prepared.

Potential design configurations for a heater head employing the radiation cooled catalytic combustor are being examined and a design for a segment of the heater head/combustor to be used in evaluation testing is being prepared. It is planned to complete assessment of the catalytic system during FY 1981. Continuation to development of a complete heater head/combustor is possible if results warrant.

A contract effort is currently in progress at Acurex Corporation to develop an analytical model for describing and predicting the coupled effects of catalytic combustion on tube surfaces and heat transfer (convection and radiation) to the tubes containing the working fluid. An existing program which treats similar phenomena will be modified to match the specific requirements of this program.

Testing has also been done on determining auto-ignition limits for premixed-prevaporized fuel-air mixtures at the inlet temperatures

and equivalence ratios pertinent to Stirling engine operation. Results obtained to date indicate residence times without ignition of the order of 10 milliseconds at one atmosphere pressure and 1300°F temperature. These residence times are shorter than obtained for the gas turbine, which operates at lower equivalence ratios. However, it appears that auto-ignition can be avoided at Stirling conditions with acceptable mixing lengths and reasonable velocities (less than one-tenth Mach number). Data from this testing are now being analyzed and correlated and a report is being prepared.

Systems Analysis

The principal objective of work at LeRC in Stirling system analysis is to develop and validate engine simulation models which will aid in the design and evaluation of automotive Stirling engines. These models will also be used to support and guide inhouse advanced component and system technology efforts, and -in company with other analytical tools- to make independent assessments of the fuel economy potential of Stirling powered vehicles.

The first generation LeRC computer model of the USS P-40 engine has been completed and is now being exercised against engine test data. Figure 11 shows engine brake power as a function of engine speed for several mean working pressures. Although the model predicts trends well, absolute power levels are generally overpredicted by the model. Several factors which may account for this are now being investigated. They include: dead volume increase due to added instrumentation not accounted for in the model, oscillatory pressure drops greater than established by steady-state calibration, and greater-than-expected auxiliary power drain. More test results will be factored into the validation effort as they are available to resolve these difficulties. Some special engine tests including operation with separately-powered auxiliaries are planned to aid in the validation effort.

Work at LeRC is also continuing concurrently on validation of the engine simulation program using GPU engine data. The correlation of these first generation models with good experimental data will provide needed insight into the magnitude of effort required to develop and fully validate later comprehensive simulation/optimization codes to be developed under the MTI engine development contract. Other independently developed Stirling engine simulation computer codes such as the Martini second order code and the Urielli third order code will also be exercised against engine test data. The results will be compared to and evaluated with respect to LeRC codes and the MTI-developed code when it is available. It is expected that the final validated Stirling engine code will incorporate the best features of the various individual codes.

Summary

As shown in Figure 1, the supporting research and technology is geared to the development schedule of the automotive Stirling engine. It is intended to be ready to provide backups or alternatives in critical areas if needed. Each SRT area is now on a timeline to be able to do this. Key efforts in each area are:

Seals- Experimental and analytical work to develop understanding of the fundamental mechanisms controlling shaft seal leakage, life, and energy dissipation is in progress.

Materials- Hydrogen permeability rates for candidate alloys at engine operating temperatures have been measured. Techniques to reduce hydrogen permeation to an acceptable level have been determined and are being refined. Material properties in high pressure and temperature hydrogen are being measured. Low cost alloys for the engine hot end will be developed.

Controls- A dynamic simulation model of the USS P-40 engine has been developed at LeRC and is now being refined and validated.

Combustors- Experiments were carried out to determine the feasibility of a combination catalytic combustor-heater head. A radiation-cooled catalytic combustor system showed promise and preparations are being made for testing of a combustor-heater head segment.

System Analysis- The first generation LeRC computer model of the USS P-40 engine has been completed and is now being exercised against engine test data. Initial comparisons are good and work is continuing to refine the model.

	FY '79	FY '80	FY '81	FY '82	FY '83	FY '84	FY '85
ADVANCED STIRLING ENGINE DEVELOPMENT	MOD I DESG. REVIEW	MOD I FIRST BUILD	MOD I DYNO. TEST	MOD I VEHICLE - EPA MOD II DYNO. TEST	MOD I VEHICLE - EPA MOD II TEST - EPA		
SEALS	ASSESS CURRENT DESIGNS	NEW SEAL CONCEPTS	RIG TEST NEW SEAL	ENGINE TEST NEW SEAL			
MATERIALS	HYDROGEN PERMEABILITY	HYDROGEN DOPANTS	LOW COST ALLOY PROPERTIES	LOW COST HOT END ENG. TEST			
CONTROLS	P-40 CONTROL MODEL		VASP CONTROL ASSESSMENT	VEHICLE CONTROL ASSESSMENT			
		MEAN PRESSURE CONTROL ASSESS.					
COMBUSTION	SINGLE TUBE TESTS COMPLETE	CATALYTIC HEATER ASSESSMENT	POSSIBLE CONTINUATION				
SYSTEM ANALYSIS	FIRST CORRELATION	MOD I CODE (MTI)	MOD II CODE (MTI)	FINAL CODE (MTI)			
		SECOND CORRELATION	ALTERNATE CODE ASSESSMENT				

Figure 1. - Stirling supporting research and technology.

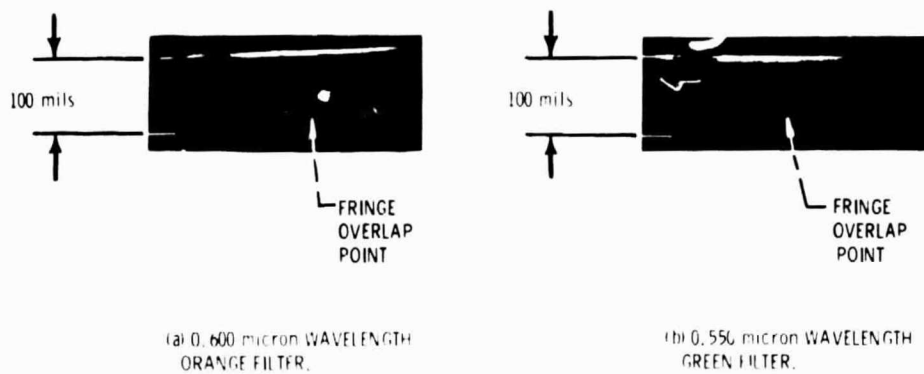


Figure 2. Interference fringe at seal-cylinder interface.

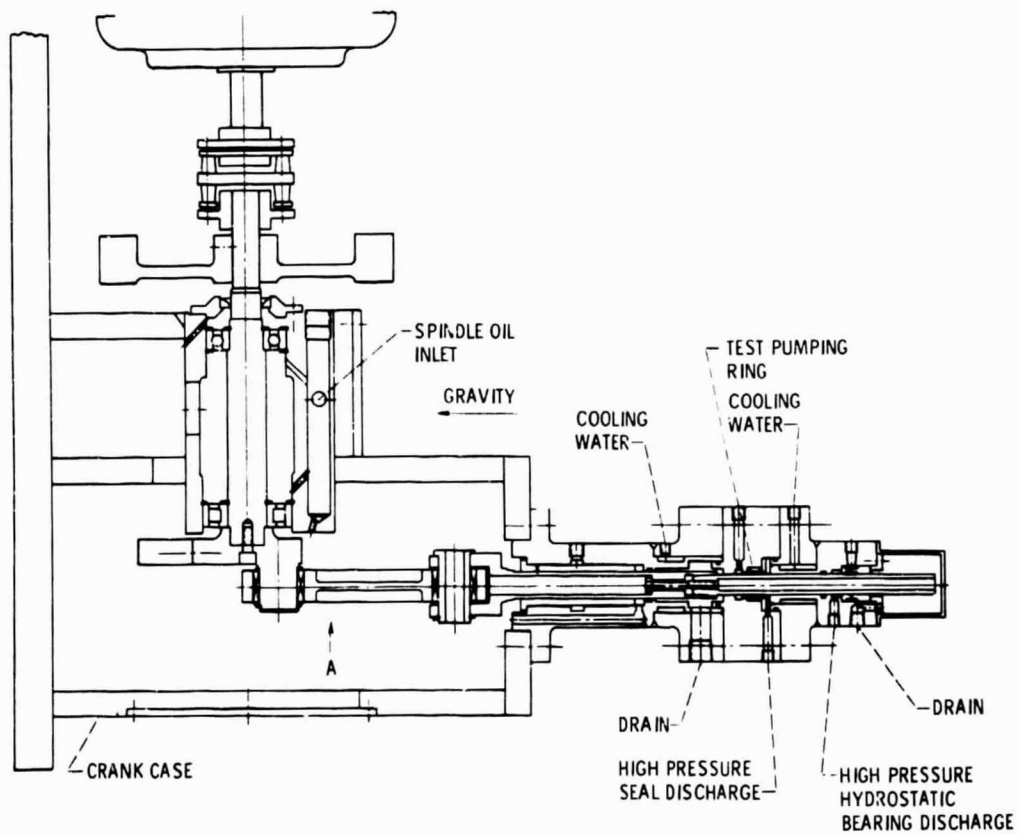


Figure 3. - Hydrodynamic oil pumping ring, seal test vehicle.

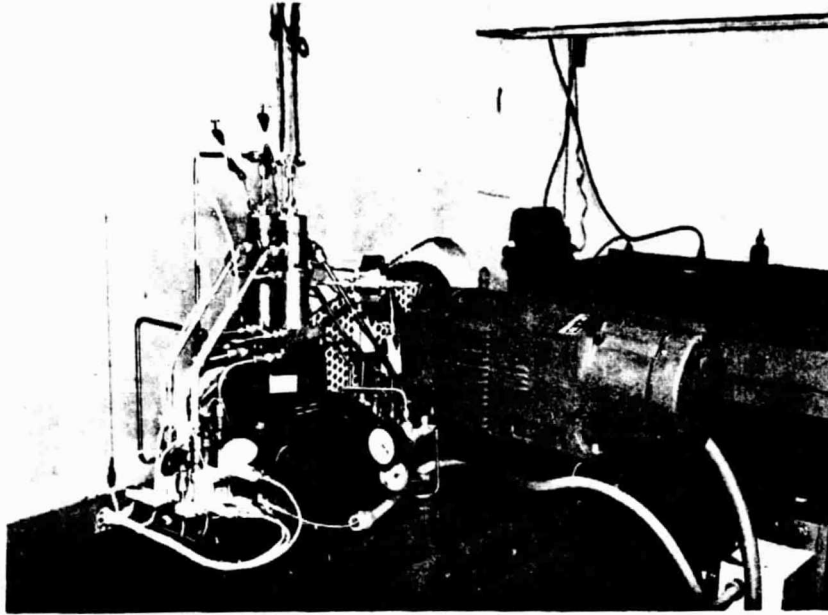


Figure 4. - LeRC seal test rig.

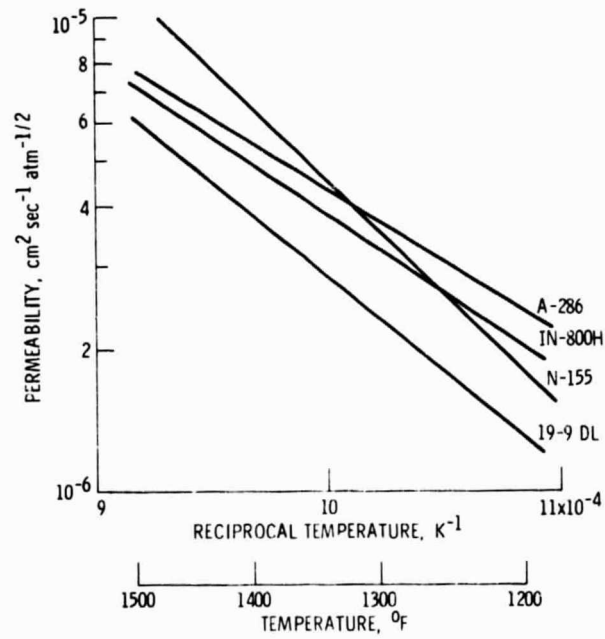


Figure 5. - Permeability rate as a function of reciprocal temperature for high-purity hydrogen and candidate heater tube alloys.

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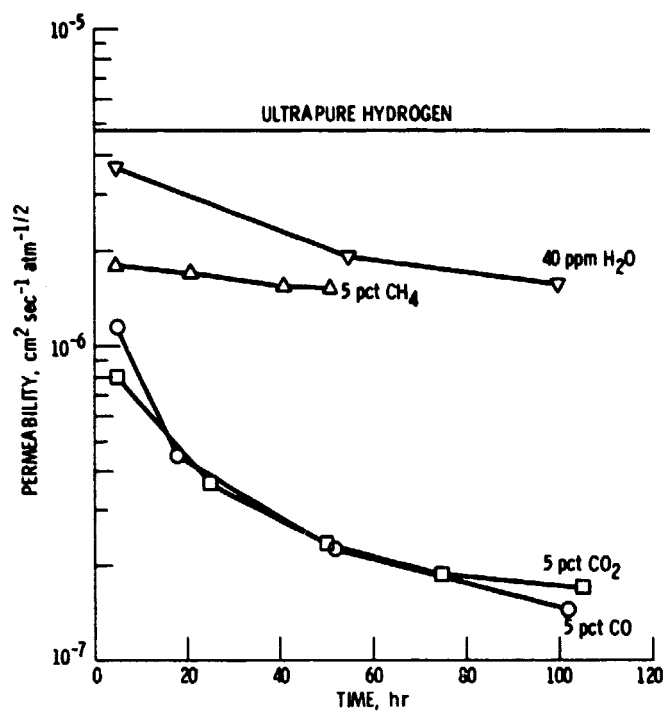


Figure 6. - Permeability of hydrogen through Inconel 800H at 760° C as a function of exposure time to hydrogen containing indicated dopant level. Permeabilities estimated from pressure losses during exposures in LeRC Stirling Simulator Rig.

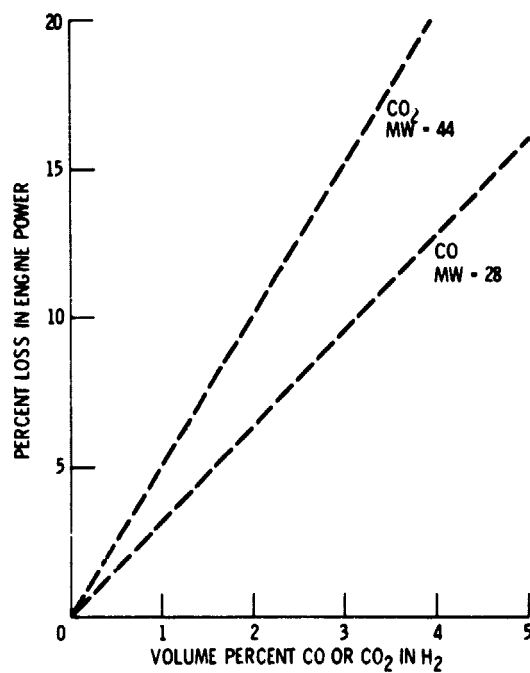


Figure 7. - Estimated engine power loss as a function of percent CO or CO₂ in working fluid due to molecular weight considerations.

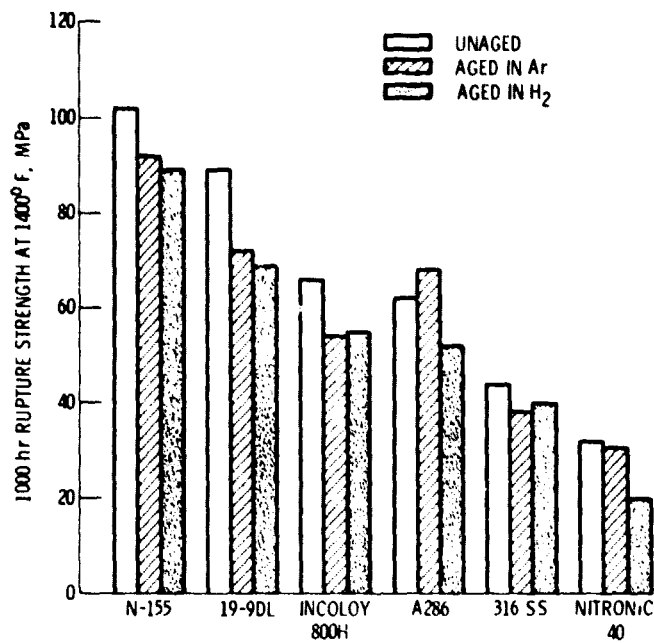


Figure 8. - Rupture strength of candidate heater tube alloys at 1400° F in air before and after aging for 3500 hours at 1400° F in 4-9 psig argon or hydrogen atmosphere.

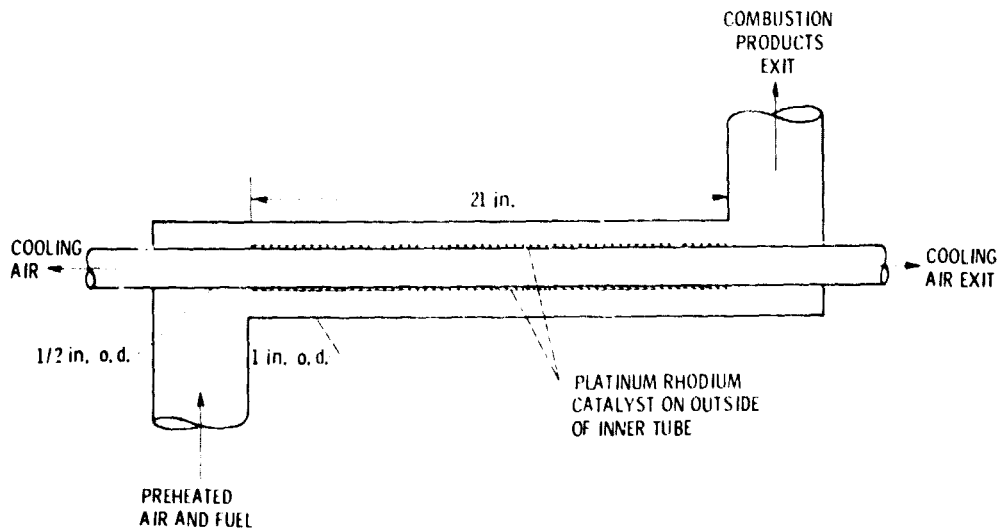


Figure 9. - Test setup for convection cooled catalyst.

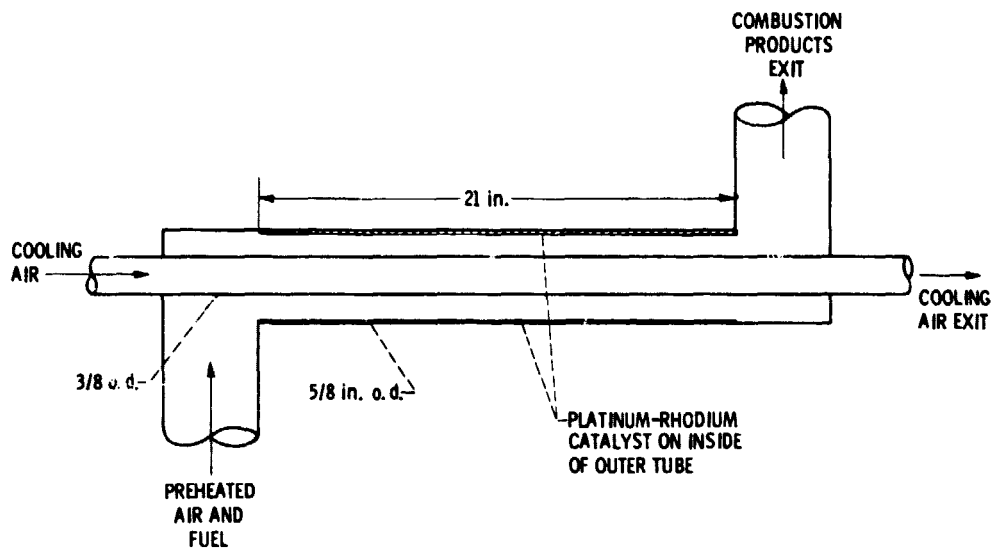


Figure 10. - Test setup for radiation cooled catalyst.

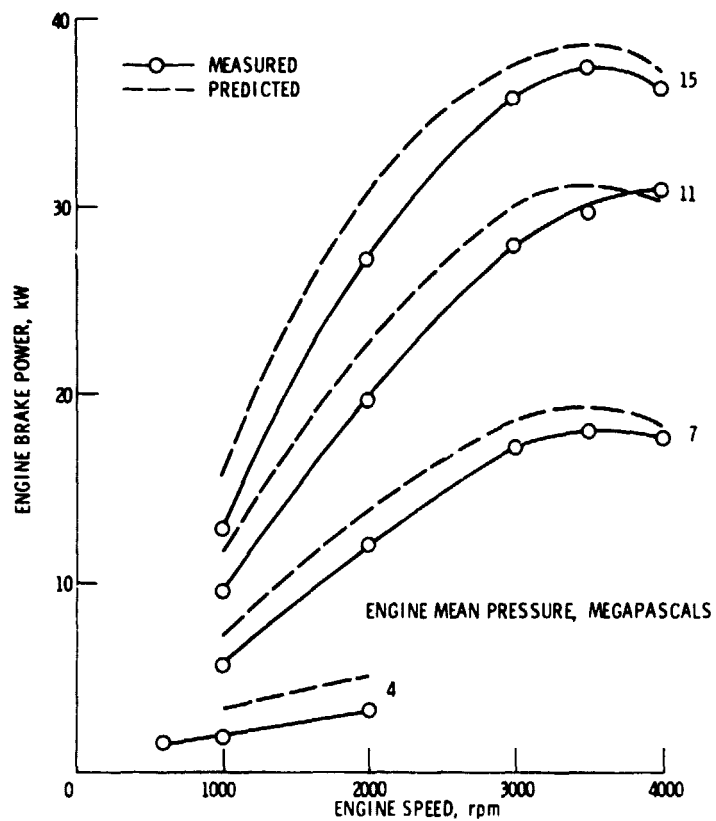


Figure 11. - Engine brake power versus speed for several operating pressures. (USS P-40 Stirling engine.)